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Optical waveguide

The invention relates to an optical waveguide according to preamble of claim 1, the optical waveguide being part of an integrated optical circuit.

The invention also relates to a method according to preamble 5 for manufacturing an optical waveguide for an integrated optical circuit.

An integrated circuit consists of a set of optical circuit elements, devices and/or external connections, which are irremovably connected to each other by optical waveguides and which are arranged onto a common support. For example, light sources and detectors, power splitters, switches, wavelength splitters and connectors, and fibre connections can be circuit elements. They have been manufactured either by the same or a different method as the optical waveguides connecting them.

The optical waveguide refers next to a three-dimensional structure arranged onto a planar support, substrate, which transfers light from one place to another in an integrated circuit. The direction of the optical waveguide in the plane of the support can be constant, or it can change either in a slowly curving or suddenly turning manner. The cross-section of the optical waveguide can be either constant, or it can change slowly or suddenly. There are often several such different optical waveguide cycles sequentially. The basic material of the support is, for example, silicon, compound semiconductor or glass. The material of the optical waveguide can be, for example, silicon, semiconductor compound, glass or organic substance.

The optical waveguide has a certain three-dimensional refractive index distribution $n(x, y, z)$, which together with material attenuation determines how light with a certain wavelength λ travels in the optical waveguide and what are its propagation losses. The used wavelength λ of light, generally optical radiation, extends from the area of visible light to near-by infrared area.

The cross-section of the optical waveguide is examined in a plane, which is perpendicular to the direction of propagation of light, the z axis or direction. The cross-section of a straight optical waveguide is constant, and its refractive index distribution $n(x, y)$ is substantially two-dimensional. On the basis of the cross-section, it is theoretically possible to calculate the number of discrete propagating modes in a straight optical waveguide, the effective refractive indexes and transverse field distributions. The calculations are usually made numerically, as no analytic solution is

generally not available. The effective refractive index describes the propagation speed of light connected to the mode along the optical waveguide in a similar way as the refractive index of the material describes the propagation speed of an optical plane wave in it. The modes can generally be divided into two groups according to their polarisation, the difference of which depends on the asymmetry of the optical waveguide and/or the birefringence of the materials. For simplifying the description, only modes of the so-called TE (quasi transverse electric) type are examined next, but all principles also apply to other polarisation modes, such as modes of the TM (quasi transverse magnetic) type. -

A special case of a straight optical waveguide is a so-called planar waveguide conductor, which has not been patterned in any way in the direction horizontal to the surface of the support, i.e. the x direction. The refractive index distribution n(y) of the planar waveguide conductor is substantially unidimensional, and it corresponds either to an infinitely wide or narrow straight optical waveguide. The number of discrete propagating modes, effective refractive indexes and vertical field distributions can be calculated for the planar waveguide conductor with the same principle as for finitely wide optical waveguides, but more simply.

The propagation of modes in a straight optical waveguide is based on the total reflection of light between the core area of the optical waveguide and the areas surrounding it both in horizontal and vertical direction. This requires that the refractive index of the core area is higher than the refractive index of the materials surrounding it. When a ridge-type waveguide or a similar structure is concerned, a so-called effective refractive index difference can prevail in the place of the refractive index difference of the materials in either direction. In practice, also specific attenuations of the materials and the scattering of light from non-ideal material interfaces also influence the propagation. In addition to propagating modes, an infinite number of so-called radiation modes can be calculated for a straight optical waveguide, to which no total reflection is connected at least at all edges of the core area. The arbitrary optical field distribution connected to the straight optical waveguide can be unambiguously presented as a weighted sum of propagating and radiation modes. The power connected to radiation modes gradually radiates away from the optical waveguide.

Other than straight optical waveguides do not generally have such propagating modes, the transverse power distribution of which remains unchanged, and which do not continuously radiate power away from the core area. On the basis of cylinder symmetry, discrete modes propagating in a curving manner can be calculated for op-

tical waveguides curving with a constant radius, but the finitely attenuating field distributions of all curving optical waveguides forcibly radiate power to the direction of the outer curve /see reference publications 1, 2/. Also the operation of other optical waveguides besides straight ones can be presented with the help of modes, but the number of modes and effective refractive indexes calculated for them, the field distributions of the modes and/or the shares of the total power of the optical waveguide in different modes change. As the cross-section changes or the direction of the optical waveguide changes, optical power is usually connected from one mode to the other. In so-called adiabatic optical waveguide structures changing sufficiently slowly in the direction of propagation, however, power is never transferred from one mode to another, but the power stays in the same optical waveguide mode slowly changing its field distribution.

It has been tried to arrange the cross-section of a straight optical waveguide so that it allows at the least the so-called fundamental mode, the mode number m of which is 0, to propagate in the optical waveguide and, most preferably, with as small losses as possible. An optical waveguide with only one propagating mode (m = 0) is called a single-moded (SM) optical waveguide. An optical waveguide with more than one propagating mode (the mode numbers m = 0, 1, 2, ...) is called a multi-moded (MM) optical waveguide. Multi-modedness does not necessarily mean that power is transferred from the fundamental mode to higher modes in the optical waveguide. Examined externally, the single-moded optical waveguide connection can consist, for example, of single-moded optical waveguide sequences and multi-moded, but adiabatic optical waveguide sequences between them /reference publication 2/. Especially in telecommunications technology, integrated optical circuits generally have to operate single-modedly, when examined externally. More complex integrated optical circuit elements (power splitters, etc.) often consist of multi-moded optical waveguide structures even in single-moded systems.

A straight optical waveguide 1; 4 is previously known, which is arranged onto a planar support 2, as is illustrated in Figures 1 and 2. The optical waveguide has a projection 1^1 ; 4^1 patterned to the core material and conveying light to a certain linear direction. The side edges of the projection need not necessarily be vertical, but they can also be, for example, oblique or rounded. Alternatively, there is provided one or several material layers between the projection and the support. On top of and at the sides of the projection there can respectively be provided one or several surface material layers 3. The material layers can either consist of solid, liquid or gaseous material. However, the refractive index distribution of the cross-section of the

optical waveguide is always such that it makes possible the existence of at least one propagating mode. Only those material layers and areas, to which the optical power distribution of at least one propagating mode extends, are generally included in the theoretical optical waveguide structure, both in the horizontal and vertical direction. At the same time, the outermost material layers and areas are assumed to extend infinitely far away.

In one known optical waveguide 1, Figure 1, the refractive index of the projection 1^1 is bigger than the refractive indexes of the surrounding materials. Irrespective of the form of the side edges, such an optical waveguide is in the following called a rectangular optical waveguide. In it light usually total reflects on the horizontal and vertical surfaces limiting the projection. If there are several material layers above or below the projection, the total reflection can alternatively occur only on some outer interface. If the layers above and below the rectangular optical waveguide have the same or at least almost the same refractive indexes, and if its side edges are vertical, the optical waveguide structure is symmetrical, besides the horizontal direction, also in the vertical direction. In this case, also the field distribution of the fundamental mode of the rectangular optical waveguide is symmetrical in the vertical direction.

In a second known optical waveguide 4, Figure 2, the projection 4^1 is seamlessly arranged onto a thin unpatterned layer of the same core material, i.e. the base element 4^2. The projection 4^1 and the base element 4^2 form the ridge-type optical waveguide 4. In the ridge-type optical waveguide, the vertical total reflection occurs on the horizontal material interfaces following the same principle as in the rectangular optical waveguide. However, the horizontal total reflection is based on the so-called effective refractive index difference /see reference publication 1/. In the case of vertical side walls, the approximative effective refractive index difference is obtained by comparing the effective refractive indexes calculated from the vertical unidimensional refractive index distributions at the place of and adjacent to the projection. However, for an exact optical waveguide analysis it is necessary to resort to two-dimensional numerical methods. The refractive index structure of the ridge-type optical waveguide is asymmetrical in the vertical direction, and because of this, also the field distribution of its fundamental mode is asymmetrical in the vertical direction. As the effective refractive index difference of the ridge-type optical waveguide decreases, for example, upon narrowing or lowering the projection, the asymmetry of its field distribution increases simultaneously in the vertical direction.

The basis in a known method, the etching method, for manufacturing one or several optical waveguides to be arranged to an optical integrated circuit is a planar support,

onto which an initially unpatterned core layer of the optical waveguide is prearranged, as well as one or several material layers. The topmost layer, the so-called resist layer, is patterned by one or several known alternative methods so that a so-called process pattern is reproduced to it as a resist mask. Known resist patterning methods are presented below. The process pattern refers to a two-dimensional pattern which determines from which areas of the support the resist will be removed and to which areas it will be left. At its simplest, the light controlling structure is a straight optical waveguide, in which the process pattern comprises a line of constant width. Generally one process pattern nevertheless presents all optical waveguide structures to be processed to one support. In the etching phase, the structure on the support is etched by using one of the several known alternative methods so that the patterned resist mask protects the parts of the material layer or layers beneath it, and the process pattern is thus reproduced to the said layers. Known etching methods are, among others, wet and dry etching. A preferable dry etching method is ICP (inductively coupled plasma) etching. If there is one or several so-called hard mask layers between the resist and core material, the etching of the structure is performed in several different phases. In this case, the pattern of the resist mask is first produced to the first hard mask layer by etching. The generated structure can then be used as a new mask in the etching of the next hard mask layer, and so on. After the patterning of the last hard mask layer, the projection is finally patterned to the core material layer by etching. Between and after the etchings, upper resist or hard mask layers can be removed by material selective intermediate etching phases. After the patterning of the projection, surface material layers can still be grown or otherwise formed on top of and to the sides of the projection.

Known resist patterning methods are, among others, optical lithography, electron beam lithography, phase mask lithography, and mechanical imprint technology. The use of the preferable optical lithography in the etching method is next described in more detail. In optical lithography, the process pattern is first formed as a patterned metal layer, i.e. as a so-called exposure mask, to the surface of a separate glass plate. A light-sensitive, such as an ultraviolet light sensitive material is used as the resist layer. A certain section of the surface of the support is covered by the metal patterns of the exposure mask, and the uncovered sections of the surface are exposed to UV light. In the development of the resist, the resist is removed either from the exposed or unexposed areas, depending on the resist process used.

The basis in a second known method, the growing method, in the manufacture of one or several optical waveguides to be arranged to an optical integrated circuit is a

support, onto which an optical waveguide with the desired properties is grown of one or several materials. In the growing method, a structure controlling the growing is usually formed to the support by using the etching method before the growing, the structure directing the growing of new material layers only to the desired places.

A drawback in the above mentioned known optical waveguides and their manufacturing methods is the deficiency in their versatility. In all of them, only one process pattern is used for determining one optical waveguide, in which case the width of the optical waveguide, the effective refractory index difference, the number of modes and the symmetry/asymmetry of the field distribution cannot be freely determined separately.

The object of the invention is to eliminate the drawbacks related to the above disclosed optical waveguides applicable to integrated optics. The object of the invention is also to achieve a new optical waveguide and a new method for its manufacture.

The optical waveguide of the invention is characterised in what is disclosed in claim 1.

The method of the invention for manufacturing an optical waveguide of an integrated optical circuit is characterised in what is disclosed in claim 5.

The dependent claims disclose advantageous embodiments of the invention.

The optical waveguide according to the invention is part of an integrated optical circuit, the optical waveguide being arranged onto a planar support and including a core element conveying light to a certain direction, the direction of propagation.

In accordance with the invention, the optical waveguide is a modified optical waveguide between the ridge-type optical waveguide and the rectangular optical waveguide, the core element in the modified optical waveguide being manufactured of the one and same material so that its cross-section transverse to the direction of propagation of light is two-stepped on both sides, and the modified optical waveguide containing two layers of different widths, the height of the first layer being equal to the height of the ridge in the ridge-type optical waveguide, and the height of the second layer being equal to the height of the base section of the ridge-type optical waveguide, the sum of the heights of the layers being equal to the height of the rectangular optical waveguide and the widths of the two layers being arranged

to change uniformly between the optical waveguides to be connected for fitting them in the lateral direction.

The core section of the optical waveguide according to the invention forms a projection in relation to the support, the both longitudinal sides of which consist of two steps, each single step being provided with an ascending wall and a stair plane, respectively. The steps are then formed of alternately repeating ascending walls and stair planes. It has to be noted that the ascending walls are not necessarily vertical, but they can be, for example, oblique or rounded. Respectively, the stair planes of the steps are not necessarily straight, especially horizontal, planes, because also they can be oblique and/or rounded. However, adjacent steps are separately identifiable, and their location is determined either on the basis of different process patterns or different process pattern combinations.

The optical waveguide of the invention is most preferably made onto a semiconductor support, especially a silicon wafer. The optical waveguide is processed onto a planar support and especially onto a light-conveying core layer on top of it, most preferably by a method of the invention.

The advantage of the invention is that with it it is possible to adiabatically change the type of the optical waveguide from a ridge-type optical waveguide to a rectangular optical waveguide. In structures with a large refractory index difference and coarsely identical dimensions larger than the wavelength, the ridge-type optical waveguide can be single-moded and the respective rectangular optical waveguide again clearly multi-moded. Because of the invention, simple variations from single-moded waveguides to multi-moded waveguides are possible both in the vertical and horizontal direction.

The advantage of the optical waveguide of the invention also is that with the help of it, the small effective refractory index difference of the ridge-type optical waveguide can be adiabatically changed to the very large effective refractory index difference of the rectangular optical waveguide.

The rectangular optical waveguides with a large effective refractory index difference have considerable advantages, compared with the ridge-type optical waveguides with a small effective refractory index difference. Using them it is, for example, possible to provide very small optical waveguide curves with small losses, and so-called optical waveguide mirrors steeply changing the direction of light and based on the total reflection of light. With them it is also possible to provide consid-

erably more propagating, especially horizontal modes to an optical waveguide of a certain width. This large number of horizontal modes can be utilised, for example, for reducing the size of so-called multi-mode interference couplers (MMI couplers), which are based on the controlled interference between horizontal modes. The length of an MMI coupler grows generally quadratically in relation to the width of an MMI optical waveguide, and the minimum of the width is again determined on the basis of the minimum number of required modes. In the rectangular optical waveguide, the large number of modes makes it possible to use clearly narrower MMI optical waveguides so that the length of the MMI coupler can be considerably shortened. When switching light to the MMI optical waveguide and away from it, it is however always necessary to make sure that light power is not coupled to the modes higher in the vertical direction at any stage.

An advantage of the optical waveguide of the invention is also that with it components based on rectangular optical waveguides can be adiabatically connected between single-moded ridge-type optical waveguides, such as small-sized optical waveguide curves, optical waveguide mirrors and short MMI couplers. Such optical waveguide connections can operate externally single-moded.

An advantage of the optical waveguide of the invention is also that in the vertical direction, i.e. in relation to the horizontal plane, the asymmetric field distribution of a ridge-type optical waveguide can be changed to a field distribution of a rectangular optical waveguide, symmetric in the vertical direction. Vertical symmetry can be utilised, among others, for decreasing the attenuation of MMI couplers and/or for reducing their size. As has been stated above, a rectangular optical waveguide is better suitable for providing short MMI couplers than a ridge-type optical waveguide. If a ridge-type optical waveguide is directly connected to the a rectangular MMI optical waveguide, the vertical asymmetry of the ridge-type optical waveguide and the vertical symmetry of the rectangular optical waveguide cause between them a detrimental coupling of light power to modes higher in the vertical direction. By using the modified optical waveguide of the invention between the ridge-type optical waveguide and the rectangular MMI optical waveguide, small MMI couplers can be connected to the ridge-type optical waveguides without the coupling problem mentioned above.

The method of the invention is directed to the manufacture of an optical waveguide of an integrated optical circuit onto a support. According to the invention, the optical waveguide is a modified optical waveguide, which is manufactured between the ridge-type and rectangular optical waveguides onto such a planar support, on which

there is provided a light conveying core layer, in which method the core layer is controllably thinned in two phases for forming two different steps on both sides of the modified optical waveguide so that during the two thinning phases a different process pattern is utilised, the edges of which determine the location of the step edges of the optical waveguide on the support so that the result is a two-step optical waveguide structure from both sides in the direction transverse to the direction of propagation of light, and in which the modified optical waveguide is provided with two layers of different widths, the height of the first layer being arranged equal to the height of the ridge in the ridge-type optical waveguide and the height of the second layer being arranged equal to the base part of the ridge-type optical waveguide, and in which the sum of the heights of the layers is arranged equal to the height of the rectangular optical waveguide, and the widths of the two layers are arranged to change uniformly between the optical waveguides to be connected for fitting them in the lateral direction. The ridge-type optical waveguide and the rectancular optical waveguide are both determined with the help of one process pattern only. However, the optical waveguide of the invention, i.e. the modified optical waveguide is determined with the help of the combination of two different process patterns.

An advantage of the method of the invention is that with it the ridge-type optical waveguide can be adiabatically changed to the rectangular optical waveguide in a reliable and easy way and with small power losses.

An advantage of the method of the invention is also that it is not especially sensitive to centering errors occurring between different process patterns.

The invention and its other advantages are next explained in more detail, referring to the enclosed drawings, in which

Figure 1 is a cross-section of a first optical waveguide according to the state of the art, i.e. a rectangular optical waveguide;

Figure 2 is a cross-section of a second optical waveguide according to the state of the art, i.e. a ridge-type optical waveguide;

Figure 3 is a cross-section of the support;

Figure 4 is a block diagram of the method for manufacturing the optical waveguide in phases;

Figures 5A and 5B illustrate the manufacture of the optical waveguide and present two different phases of readiness;

Figure 6 is a perspective view of the optical waveguide of the invention, with the help of which the ridge-type optical waveguide can be converted to the rectangular optical waveguide, or vice versa; and

Figures 7A, 7B, 7C are cross-sections A-A, B-B and C-C of the optical waveguide in Figure 6, respectively.

The invention relates to an optical waveguide, which is part of an optical integrated circuit. The optical waveguide has a core element conveying light to a certain direction, the direction of propagation. The optical waveguide, especially its two-step core element, is arranged onto a planar support 7, Figure 3. The refractive index of the layer or material below the core element on the wavelength in question is smaller than the corresponding refractive index of the core element. For example, a *photolithographic method, Figure 4, is used in the manufacture of the optical* waveguide of the invention, the method being explained in more detail later in this application.

In an advantageous embodiment of the invention, the common support is most preferably a support made of semiconductor, such as a semiconductor wafer that is generally used also as a support for electronic integrated circuits. The support works as a physical foundation, onto which a number of integrated optical circuits are arranged.

The support 7 of the optical waveguide, Figure 3, is preferably a SOI (silicon on insulator) wafer. The SOI wafer consists of a thick silicon wafer 7a, on which there first is a thin silicon oxide layer 7b, and on top of that a thin core layer 7c of silicon. The oxide layer 7b acts as a so-called buffer layer, which optically insulates the core layer 7c from the silicon wafer below, due to its refractory index, which is smaller than that of silicon. The thickness of the oxide layer 7b is typically 0.5 – 3 μm, but it can also be as much as 1 – 15 μm. The refractory index of silicon is about $n = 3.5$ and, respectively, the refractory index of silicon is about $n_a = 1.5$, depending on the wavelength of light. The wavelength λ of the light used is about 1 – 2 μm, preferably, for example, 1.55 μm. Figure 3 expressly presents a SOI wafer, but alternatively, also several different single- or multi-layer structures can be used as the support. Instead of silicon, for example, gallium arsenide (GaAs) or other respective material can be alternatively used as the material for the core layer.

In the method of the invention, the optical waveguide 60, Figure 6, is manufactured onto a suitable finished support 7, Figure 3, such as a SOI wafer, on which there already is a light conducting core layer 7c. In the method of the invention, the optical waveguide 60, especially its core element 600, is made so that the core layer 7c on the support is controllably thinned in two different phases for forming the different steps 6; 6^{1a} 6^{2a} 6^{3a} 6^{1b} 6^{2b} 6^{3b} and the layers 60^1, 60^2, a different process pattern being utilised in both thinning phases, the area dimensions of which, i.e. width and length, correspond to the area dimensions of the different layers of the optical waveguide so that the result obtained is an optical waveguide structure two-step from both edges, transverse to the direction of propagation of light. Thus, the edges of the different process patterns determine the location of the edges of the steps of the optical waveguide in the core layer 7c on top of the support. In the same connection, also other possible integrated optical waveguides related to the optical waveguide 60 are prepared.

The optical waveguide 60 of the invention is illustrated as a perspective view in Figure 6, and its cross-sections are illustrated in Figures 7A, 7B and 7C. The optical waveguide 60 is a modified optical waveguide, which is arranged between the ridge-type optical waveguide 61 and the rectangular optical waveguide 62, which are known as such.

In the optical waveguide 60 of the invention, there are two successive and seamless material layers 60^1, 60^2 made of the same material, which form the core element 600. The layers 60^1, 60^2 of the optical waveguide 60 have different widths l_{60a}, l_{60b} so that the steps 6; 6^{1a}, 6^{2a}; 6^{1b}, 6^{2b} are formed to the edges 60a, 60b of the optical waveguide 60. The optical waveguide 60 can also be surrounded by a surface layer, i.e. shell (not shown in the figures). This shell can be made of a suitable solid material, which is added onto the optical waveguide 60 in connection of the manufacture, or it can be a gaseous shell, such as surrounding air, or even a liquid shell. The shell can also consist of more than one layer or material.

The optical waveguide 60 of the invention is made onto the planar support 7, as has been shown above. The two-step patterning of the core layer required in the realisation can be made, for example, by using the photolithographic manufacturing method described next, presented as a block diagram in Figure 4. Some manufacturing phases have been illustrated in Figures 5A and 5B. However, it has to be noted that the optical waveguide 60 of the invention can also be realised by many other alternative methods.

As the optical waveguide 60 of the invention is manufactured using the photolithographic manufacturing method, the support 7 is first taken, to the core layer 7c on top of which the optical waveguide is intended to be arranged (phase 40). The support is a preprocessed wafer, for example, a SOI wafer (cf. Figure 3). In the first manufacturing phase 41, a hard mask layer 9; 9^1, such as a silicon dioxide layer, is added to the surface of the wafer. In the second phase 42, a resist, i.e. a light-sensitive protective layer 10; 10^1 (cf. Figure 5A) is added on top of the hard mask layer 9; 9^1. After this, in phase 43, the preprocessed wafer with the first process mask, i.e. in this case the exposure mask 11; 11^1 is fitted to an exposure device, in which the support 7 and the process pattern 11 are located parallel to and at a small distance from each other, and they are exposed (cd. Figure 5B). In this case, the light 12, especially UV light, is let to affect the surface layers of the support and especially the light-sensitive protective layer 10; 10^1 through the apertures $11a^1$, $11b^1$ of the exposure mask 11; 11^1. Thus, a picture of the exposure mask, especially its edges, is arranged to the surface of the wafer. In the next fourth phase 44, the exposed wafer is developed so that the exposed parts of the light-sensitive film are detached. After this, the wafer is etched in the fifth phase 45 so that of the areas that became unexposed in the development, first the hard mask layer and then the first grooves 13, 14 can be etched to the desired depth h_1. The etchings of the hard mask and the core layer are generally separate process phases, although they have been shown here as one phase for the sake of simplicity. After the etching, the first projection 15 remains between the grooves 13, 14, the height of the projection being h_1 and the width l_1. In the sixth phase 46 the resist 10; 10^1 is removed. In the seventh phase 47, the hard mask layer 9; 9^1 is removed from the unetched areas. Thus, the first processing cycle $q = 1$ has been performed, and it is possible to move to the second processing cycle $q = q + 1$.

The second processing cycle begins principally in the same way as the first processing cycle: a new hard mask layer is first added onto the support already once processed, and the light-sensitive protective layer is also added onto the hard mask layer, i.e. the first and second phase 41, 42 are performed again. After this one moves to the third phase 43, and the exposure with the second process mask, i.e. in this case, the exposure mask, is performed. The light is again let to influence the surface layers of the support through the apertures of the second exposure mask. In the fourth and fifth phase 44, 45, the support is again developed and etched, as the result of which in this application example, all the areas exposed during this second processing cycle are etched until the lower edge of the core layer. The resist is then removed in the sixth phase 46 and the hard mask layer in the seventh phase 47. Thus,

also the second processing cycle $q = 2$ has been performed, and the core layer of the optical waveguide 60 is etched to form a two-step layer.

In the photolithographic manufacturing process described above, a separate hard mask layer is presented to be added at the beginning of both processing cycles and, respectively, to be removed at the end of the same processing cycle. However, this is not always necessary, but the same hard mask layer can be used in both processing cycles. In this case, the deepening of all the grooves already made is continued during the latter processing cycle, and the etching of new grooves is further initiated.

The etching depths and the widths of the projections restricted by the etched grooves are typically between 0.5 – 15 μm with a support that is a SOI wafer.

In the manufacture of the optical waveguide of the invention described above, each material layer and the respective step of the optical waveguide were made successively, beginning from the uppermost layer and the respective step 6^{1a}, 6^{1b}. However, the order of the processing cycles and, at the same time, the order of use of the process patterns can be changed. It especially has to be noted that some areas can be overecthed so that the sum of the etching depths in these is bigger than the original thickness of the core layer. In this case, the possible continuation of the etching to the layers below the core layer depends on the materials of the layers in question and on the etching method used.

The structure of the optical waveguide 60 of the invention is next explained in more detail referring to Figures 6, 7A, 7B, 7C.

The height of the uppermost layer of the optical waveguide 60, i.e. the first layer 60^1 and at the same time the rise h_{60a} of the uppermost step is equal to the height h_h of the ridge 61^1 of the ridge-type optical waveguide 61. The first end of the optical waveguide 60 is connected to the ridge-type optical waveguide 61 and the second end to the rectangular optical waveguide 62. At the connecting point 601 of the optical waveguide 60 and the ridge-type optical waveguide 61, the width $l_{60a} = l_{601a}$ of the first layer 60^1 of the optical waveguide 60 is equal to the width l_h of the ridge 61^1 of the ridge-type optical waveguide. At the connecting point 602 of the optical waveguide 60 and the rectangular optical waveguide 62, the width $l_{60a} = l_{602a}$ of the first layer 60^1 of the optical waveguide 60 is equal to the width l_s of the rectangular optical waveguide 62. At the connecting points 601, 602 of the waveguides there is no material connecting area or similar, but the core elements consisting of the layers

of different waveguides are of the same material, and they connect to each other directly and seamlessly.

In the application example of Figure 6, the width l_h of the ridge 61^1 of the ridge-type optical waveguide 61 is smaller than the width l_s of the rectangular optical waveguide 62. Alternatively, depending on the application, the width l_h of the ridge 61^1 is equal to or bigger than the width l_s of the rectangular optical waveguide 62. The width l_{60a} of the first layer of the optical waveguide 60 is thus arranged to change from the first width l_{601a}, which is equal to the width l_h of the ridge 61^1 of the ridge-type optical waveguide at the first connecting point 601, to the second width l_{602a}, which is equal to the width l_s of the rectangular optical waveguide 62 at the second connecting point 602.

The height h_{60b} of the second layer 60^2 of the optical waveguide 60 and at the same time the rise of the second step is equal to the height h_k of the base part 61^2 of the ridge-type optical waveguide 61. At the connecting point 601 of the optical waveguide 60 and the ridge-type optical waveguide 62, the width $l_{60b} = l_{601b}$ of the second layer 60^2 of the optical waveguide is equal to the finite width l_{61k} of the base part 61^2 of the ridge-type optical waveguide. At the connecting point 602 of the optical waveguide 60 and the rectangular optical waveguide 61, the width $l_{60b} = l_{602b}$ of the second layer 60^2 of the optical waveguide 60 is equal to the width l_s of the rectangular optical waveguide 62. The width l_{61k} of the base part 61^2 of the ridge-type optical waveguide 61 is in principle infinite, but in practice, the second optical waveguide 60 and its second layer 60^2 are connected to the base part 61^2 at the connecting point 601 in some suitable finite width, which is so large that it has no significant influence on the activity of the optical waveguide. Preferably the width l_{61k} is the width l_h of the ridge 61^1 multiplied by a constant figure, which is calculated numerically.

The height h_{60a} of the first layer 60^1 of the optical waveguide 60 of the invention is thus equal to the height h_h of the ridge 61^1 of the ridge-type optical waveguide, as again the height h_{60b} of the second layer 60^2 is equal to the height h_k of the base part 61^2 of the ridge-type optical waveguide. The height h_s of the rectangular optical waveguide 62 again is the sum of the heights h_{60a} and h_{60b} of the layers 60^1, 60^2 of the second optical waveguide 60, i.e. $h_s = h_{60a} + h_{60b} = h_h + h_k$.

The heights h_{60a}, h_{60b} of the layers 60^1, 60^2 of the optical waveguide 60 according to the invention and thus the rises of the steps depend on the height dimensions h_h, h_k of the ridge 61^1 and the base part 61^2 of the ridge-type optical waveguide 61 and, re-

spectively, on the height h_s of the rectangular optical waveguide 62. As is evident from above, the first layer 60^1 of the optical waveguide 60, i.e. the distance of the inner step pair is arranged to narrow (or to widen, respectively) in the direction of travel of light most preferably uniformly and linearly from one width l_h to second width l_s (or vice versa, seen to the opposite direction of propagation of light).

The purpose of the optical waveguide 60 is to connect two optical waveguides 61, 62 of different shapes and at least partly with different dimensions to each other. By applying the optical waveguide 60 of the invention, this is achieved adiabatically in a desired way with as small light propagation losses as possible. In the embodiment example shown, the optical waveguide 60 and the optical waveguides 61, 62 connected by it are symmetrical in relation to their vertical middle plane.

The manufacture of the optical waveguide 60 and the ridge-type optical waveguide 61 and the rectangular optical waveguide 62 connected to it is performed by utilising two, the first and second exposure masks 66, 67 or a corresponding process pattern in two successive processing phases. In Figure 5, the exposure masks 66, 67 are illustrated at a distance above the support 7 and the second optical waveguide 60 of the invention arranged on it. The next more detailed description of the exposure masks 66, 67 is based on the assumption of the use of the photolithographic patterning described above. However, the same or similar masks can also be applied in connection of other patterning methods.

The width l_{66a} of the first end 66a of the first mask 66 corresponds to the width l_h of the ridge 61^1 of the ridge-type optical waveguide 61. From the mask point 601a corresponding to the first connecting point 601, the first mask 66 widens towards the second end 66b, and its width l_{66} is equal to the width l_{60a} of the first layer 60^1 of the optical waveguide 60 connecting the ridge-type optical waveguide 61 and the rectangular optical waveguide 62 until the mask point 602a corresponding to the second connecting point 602, from which onwards it in this embodiment widens further in a similar way as between the mask points 601a, 602a. To the direction shown after the second mask point 602a, i.e. to the direction of the rectangular optical waveguide 62, the width l_{66b} of the first mask 66 is bigger than the width l_s of the rectangular optical waveguide 62 to be processed, and its size is of no significance as such; the rectangular optical waveguide 62 is restricted to its final width l_s with the help of the second exposure mask 67, as is evident from the following explanation.

The width l_{67b} of the second end 67b of the second exposure mask 67 corresponds to the width l_s of the rectangular optical waveguide 62. The second mask 67 widens from the mask point 602b corresponding to the second connecting point 602 towards the first end 67a, and its width l_{67} is equal to the width l_{60b} of the second layer 60^2 of the optical waveguide 60 connecting the ridge-type optical waveguide 61 and the rectangular optical waveguide 62 until the mask point 601b corresponding to the first connecting point 601, from which onwards it in this embodiment widens further in a similar way as between the mask points 601b, 602b. To the direction shown after the first mask point 601b, i.e. to the direction of the ridge-type optical waveguide 61, the width l_{67a} of the second mask 67 is so much bigger than the width of the ridge-type optical waveguide 61 that its size has no significant influence on the activity of the optical waveguide. Thus it can be said that at the connecting point 601, the width l_{67a} of the second mask 67 corresponds to the finite width of the base part 61^2 of the ridge-type optical waveguide 61.

Because the width l_{67} of the second mask 67 at the first connecting point 601 has no significant influence on the activity of the optical waveguide, the location of the first connecting point 601 is determined only on the basis of the mask point 601a of the first mask 66 corresponding to it. The width l_{66b} of the first mask 66 from the second connecting point 602 towards the rectangular optical waveguide 62 again has no influence on the activity of the optical waveguide as long as it is bigger than the width l_{67b} of the second mask 67 at the respective place. The location of the second connecting point 602 is solely determined on the basis of the intersection points of the edges of the masks 66, 67. In Figure 6, the connecting point 602 is drawn to become congruent with the mask point 602b for simplicity, but this need not necessarily be the case. For example, the second mask 67 can continue to narrow for a short range onwards from the mask point 602b towards the rectangular optical waveguide 62 so that also the rectangular optical waveguide connected to the optical waveguide 60 narrows respectively.

Because of the finite mask alignment accuracy, the masks 66, 67 or the respective process patterns can slightly move in relation to each other as the optical waveguide is being manufactured. However, the operation of the optical waveguide 60 does not significantly change because of small alignment errors, because on the basis of what has been said above, it is not necessary to align any mask points to each other in an absolutely accurate manner. At most, the alignment errors slightly move the connecting points 601 and 602 in the longitudinal direction of the optical waveguide and make the optical waveguide 60 slightly asymmetrical in relation to its longitudi-

nal middle axis. By using mask patterns that widen and narrow sufficiently flatly, the optical waveguide 60 stays sufficiently adiabatic also in this case.

The first and second exposure mask 66, 67 are used in the manufacture of the optical waveguide 60 and the related optical waveguides 61, 62. In the manufacture, in the etching step of the first processing cycle following the use of the first mask 66 the etching is performed to the first depth $h_1 = h_h = h_{60a}$ so that the first layer 60^1 of the optical waveguide 60 and the ridge 61^1 of the first ridge-type optical waveguide 61 can be separated from the core layer 7c on the support 7. The areas 64a, 64b removed in the first etching step are marked with broken lines in Figures 7A, 7B and 7C. In the etching step of the second processing cycle following the use of the second mask 67 the core layer is etched so that at the edges of the rectangular optical waveguide the etching extends through the whole core layer (to the depth h_s), and at the same time, the second layer 60^2 of the third optical waveguide 60 is overetched through the remaining thickness h_{60b} of the core layer. The second etching depth h_2 of the second etching phase is different in different areas, due to overetching. The areas 65a, 65b removed in the second etching step are marked with broken lines in Figures 7B and 7C.

The optical waveguide 60 of the invention can also be realised by using a preferable first varied manufacturing method, compared with the previous method. In this case, the exposure masks 66 and 67 are used in reverse order in relation to the previous method, and in addition, a common hard mask layer is used in connection of them. Thus, the removal of the hard mask and the adding of a new hard mask is passed between the processing cycles. In the etching step of the first processing cycle following the use of the mask 67, the core layer is etched to the depth h_{60b}, and in the etching step of the second processing cycle following the use of the mask 66, the core layer is etched to the depth h_{60a}. The latter etching step continues the etching of all areas etched in the first processing cycle (the edges of the rectangular optical waveguide and the edges of the second layer of the optical waveguide 60) until the lower edge of the core layer and, simultaneously, it etches the areas 64a and 64b surrounding the ridge-type optical waveguide and the areas between the adjacent steps 6; 6^{1a}, 6^{2a} and 6; 6^{1a}, 6^{2a} to the depth $h_h = h_{60a}$. With this method, the final result obtained will be the same structure as with the previous method, but in this way each etching phase etches to the same depth in all areas, and thus such an overetching phase is avoided, in which the etching in some areas tends to pass the lower edge of the core layer.

In relation to what is explained above, the optical waveguide 60 can also be realised with the help of a second and third preferable varied manufacturing method. In the second varied manufacturing method, the width l_{60b} of the second layer of the optical waveguide 60 and the width l_{67} of the second mask 67 corresponding to it are arranged as a constant, which is bigger than the width l_h of the ridge of the ridge-type optical waveguide 61, which is equal to the width l_s of the rectangular optical waveguide 62. In this case, the width l_{60a} of the first layer of the optical waveguide 60 and the width l_{66} of the first mask 66 corresponding to it are arranged to widen from the width of the first mask point 601, i.e. the width l_h of the ridge of the ridge-type optical waveguide 61 towards the rectangular optical waveguide. In a third varied manufacturing method, the width l_{60a} of the first layer of the optical waveguide 60 and the width l_{66} of the first mask 66 corresponding to it are arranged as a constant, which is equal to the width l_s of the rectangular optical waveguide 62 at the second connecting point 602. In this case, the width l_{60b} of the second layer of the optical waveguide 60 and the width l_{67} of the second mask 67 corresponding to it are arranged to narrow from the width of the first mask point 601, i.e. the finite width l_{61k} of the base part 61^2 of the ridge-type optical waveguide 61 towards the rectangular optical waveguide and slightly past the second mask point 602 so that no very high requirements be set to the mask alignment. In the second and third varied manufacturing method, the other dimensions of the optical waveguide 60 are kept the same and/or they are arranged to change, as is explained above in connection of Figures 6, 7A, 7B and 7C.

A considerable advantage of the optical waveguide 60 and its manufacturing process is that no especially large alignment accuracy is needed between the two process patterns used, as has been demonstrated above. Only one process pattern, or a corresponding mask, determines the dimensions (i.e. especially the width and the length, but, in principle, also the height) of the optical waveguide 61, 62 to be connected to the optical waveguide 60 of the invention. Because of the adiabatic property of the optical waveguide 60 and the small angles of crossing of the edges of the process patterns, small alignment errors do not largely influence the transfer of light between the optical waveguides 61, 62 to be connected.

The invention is not limited to concern the above presented embodiment examples only, but many variations are possible within the inventional idea determined by the claims.

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